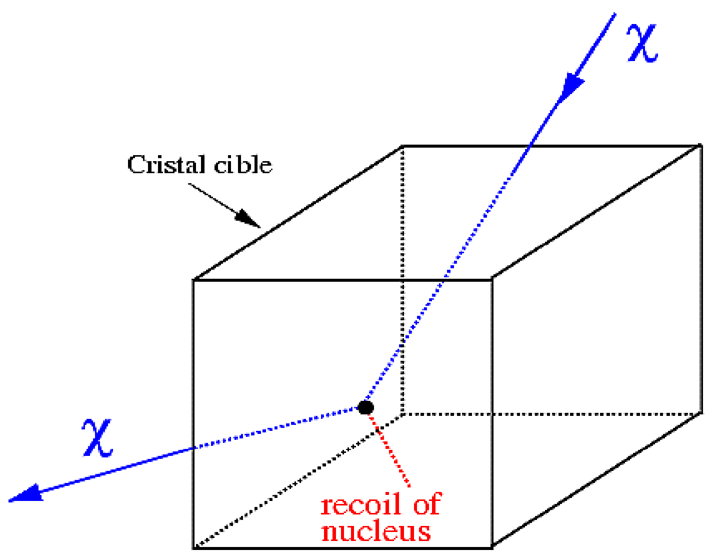
A new generation detector for supersymmetric particles search by direct detection : MACHe3

Emmanuel Moulin, D. Santos, G. Perrin, G. Duhamel, F. Naraghi, Yu.M. Bunkov, H. Godfrin

A new generation detector for supersymmetric particles search by direct detection : MACHe3, MAtrix of Cells of superfluid Helium 3



ISN-CRTBT collaboration:

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Main topics :

- Cosmological evidence for cold non-baryonic dark matter

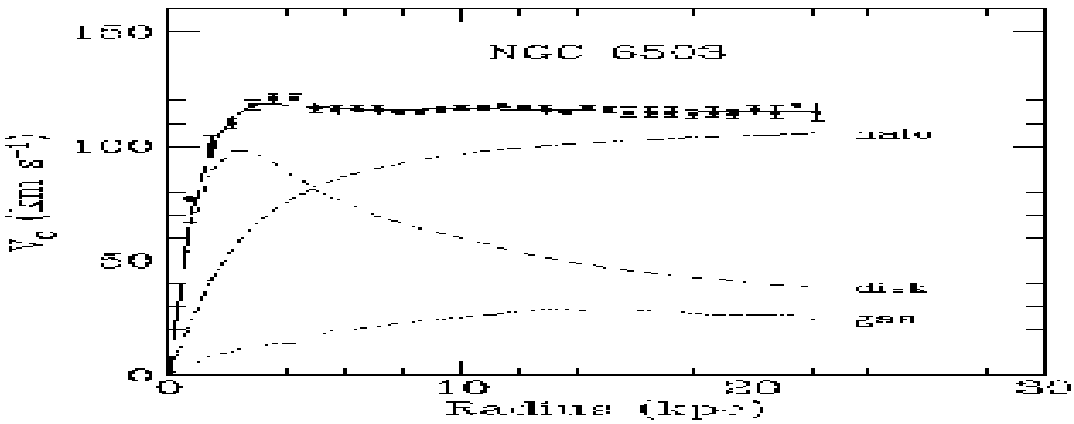
- WIMP candidate : the neutralino

- MACHe3 project :
  - detection principle
  - detection threshold
  - events

- Results :
  - neutrons spectrum
  - simulation of muons (with GEANT3.21)
  - muons spectrum

- Conclusions and prospects

Evidence for non-baryonic dark matter :



$$\Omega_{tot} = \Omega_\gamma + \Omega_\Lambda + \Omega_M \,,$$
$$\Omega_{tot} \sim 1 \;\; \text{(CMB)}$$

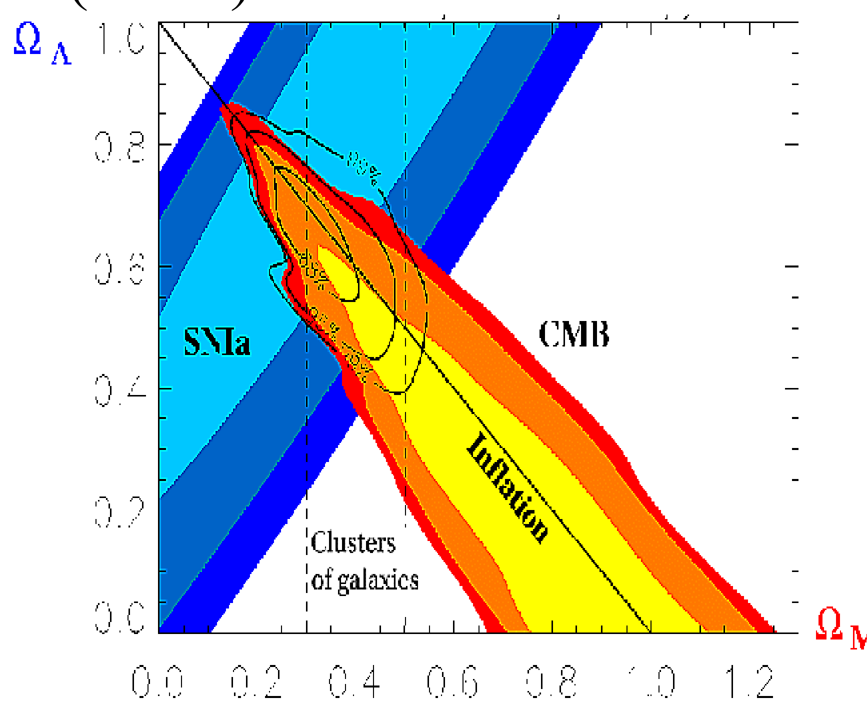
$\Omega_\gamma \sim 5{\times}10^{-5}$
negligible

$\Omega_\Lambda \sim 0.7$ (SNIa)

$\Omega_M \sim 0.3$
(clusters of galaxies)

$\Omega_B \sim\ 0.04$ (BBN) :

$\Omega_B < \Omega_M$



$$\Omega_M = \Omega_B + \Omega_{HDM} + \Omega_{CDM}$$

$\Rightarrow$ existence of non-baryonic dark matter :

- hot, ‘‘HDM’’ : neutrinos, $\Omega_\nu \leq 0.09$
- cold, ‘‘CDM’’ : WIMPs

WIMPs candidate for cold non-baryonic dark matter : the neutralino χ

- cold non-baryonic dark matter is favoured (structures formation in the Universe)

- characteristics of WIMPs (Weakly Interactive Massive Particles) :
  - masses : from 30 GeV/c^2 up to few TeV/c^2
  - weak cross section : $< 10^{-2}$ pb
  - neutral of charge and color

- SUSY $\Rightarrow$ lightest supersymmetric particle (LSP) : the neutralino χ (with R-parity conserved)
  - belongs to WIMPs' class
  - its relic density: $\Omega_\chi = O\ (10^{-1})$

MACHe3 project for neutralinos χ detection from galactic halo :

- Measure of energy deposited by elastic scattering of χ on ^{3}He target nucleus

- ^{3}He as sensitive medium :
  - superfluid ^{3}He : T ~ 100 μK
  - very low energy gap of quasiparticles : threshold of 1 keV
    ⇒ ability of detecting weak recoil energies

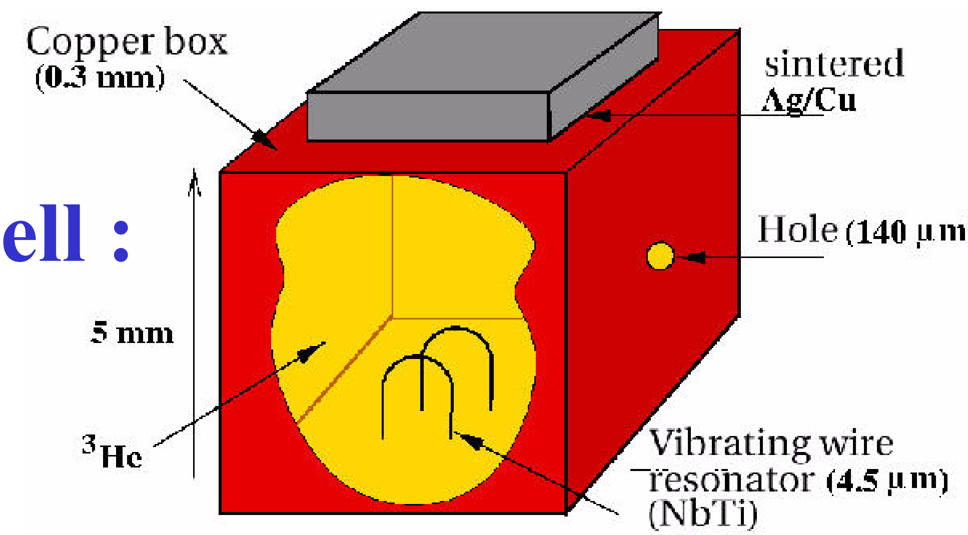
- Main contributions to the background :
  - ➢ gammas, neutrons, muons
  - ➢ protons, α particles (negligible)
  - ➢ micro-vibrations

- Main interesting features :
  - ➢ high purity ^{3}He
  - ➢ spin 1/2 (axial interaction)
  - ➢ neutron capture process
  - ➢ low sensitivity to γ

CRTBT experimental hall :

- cryostat
- 5 cm thick
  lead shield

Bolometer cell :



- Operating mode : Lancaster type bolometer
  damping effect on the vibrating wire of the quasiparticles cloud produced by an incoming particle interacting inside the cell
- Measure : damping linked to the frequency width
  of the vibrating wire calibrated in energy
- Thermal diffusion through the hole

χ event in the granular detector :

- 2 contributions to the elastic scattering on nucleon :
  - scalar interaction : $\sim 10^{-6}$ pb
  - axial interaction : $\sim 10^{-2}$ pb

- Elastic scattering on ^{3}He nucleus :

$$E_{recul}^{max} = 2\frac{m_{^3He} M_\chi^2}{\left(m_{^3He} + M_\chi\right)^2} v^2 \cong 2 m_{^3He} v^2$$

$\Rightarrow$ χ event defined by an energy deposit $\leq$ 6 keV

- The whole energy is deposited in a single cell

$\Rightarrow$ systematic discrimination compared with other events

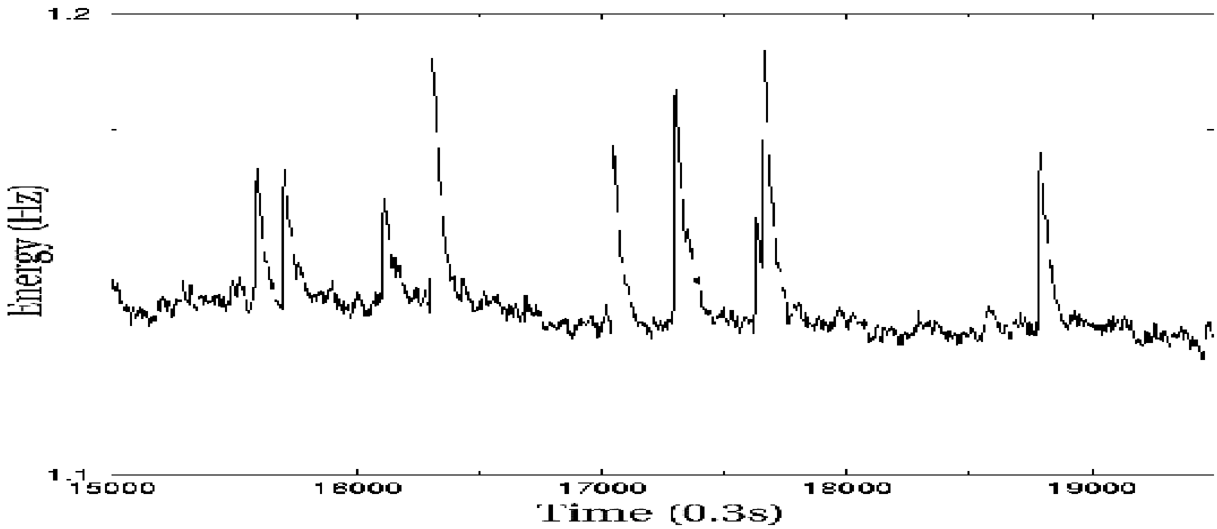
- Expected event rate :

$R = 1400 \times \sigma\,(\mathrm{pb}) / M\chi\,(\mathrm{GeV/c^2})\ [\mathrm{kg^{-1}\ day^{-1}}]$

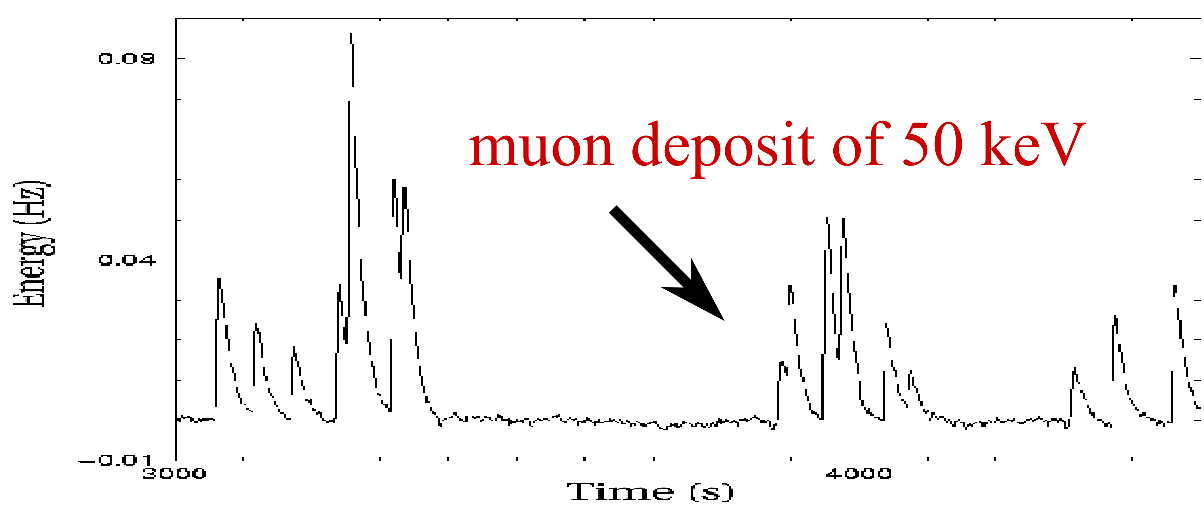
With $\sigma \sim 10^{-2}$ pb and $M\chi \sim 30$ GeV/c^2

$\Rightarrow R \sim 7 \times 10^{-2}\ \mathrm{kg^{-1}\ day^{-1}}$

Raw data at 100 μK :

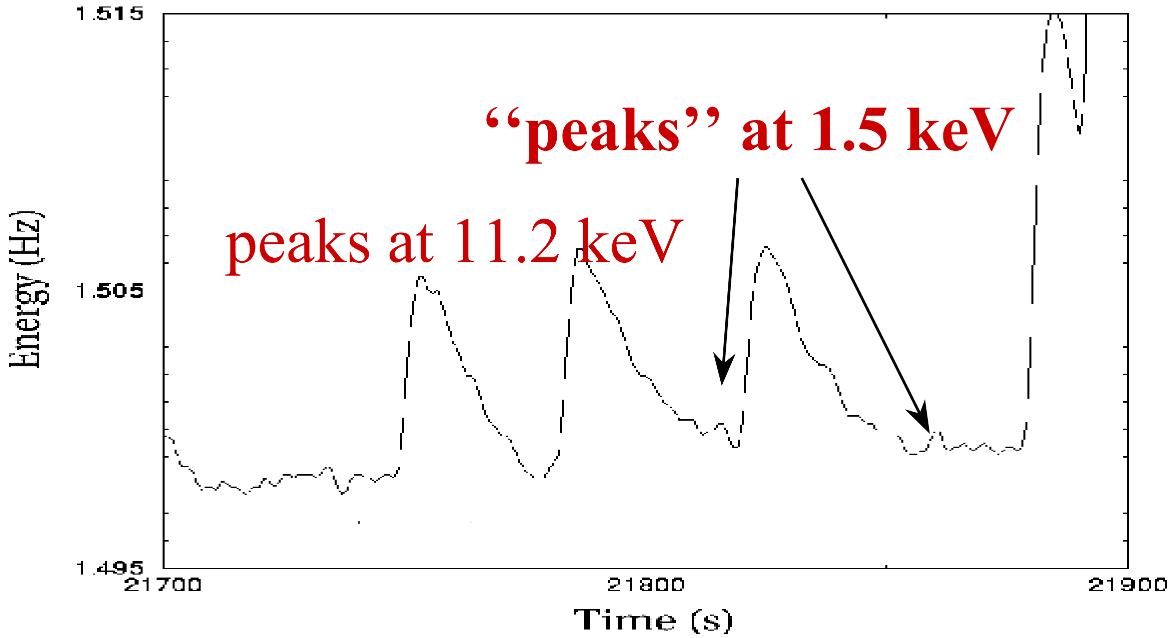


- low frequency modulation
- micro-vibrations



- very low micro-vibrations

Sensitivity of the cell :



Acquisition spectrum at 100 µK, without source :
- 3 peaks of about 10 keV
- detection of structures of about 1 keV

⇒ very promising results and :
- improvement of acquisition system
- understanding of micro-vibrations

Discrimination of the different contributions of background for WIMPs detection :

- γ rays (natural radioactivity) :
  ^{40}K, ^{214}Bi, ^{214}Pb, ^{220}Ac et ^{222}Rn
  ➔ Compton effect >> photoelectric effect :
  $\sigma_{com} / \sigma_{pho} \sim 10$ (at 100 keV)

- neutrons (considered as ultimate noise) :
  ➔ neutron capture process by the target nucleus, enhanced after thermalization :
  $\sigma_{cap} / \sigma_{ela} \sim 10$ (at 1 keV)

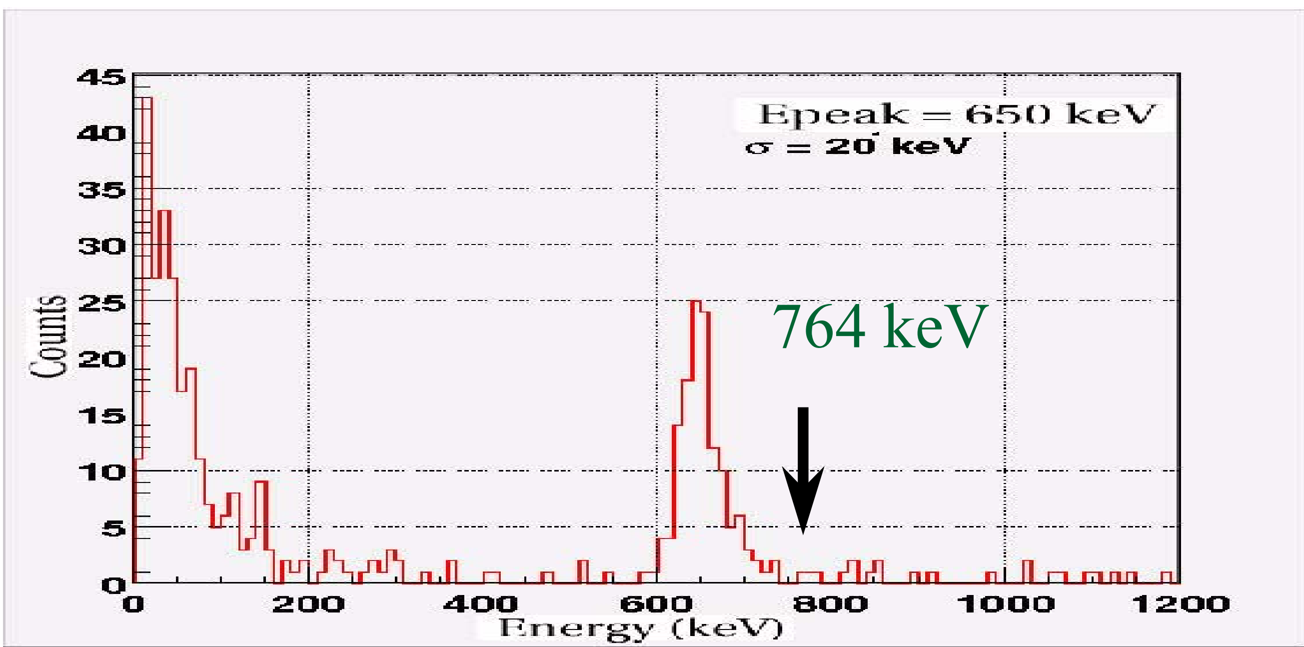
- cosmic muons (energy ~ 2 GeV) :
  ➔ energy loss in ^3He by ionization
  $dE/dx \sim 0.1$ MeV/cm

Neutrons separation by capture process by ^{3}He nucleus :

- Neutron capture : exoenergetic reaction

$$n + {}^3He \longrightarrow p + {}^3H + 764\ keV$$

- Experiments with Am/Be source
- Acquisition time : 4.6 h, à 100 µK



- Position of the peak : 650 keV, width 20 keV

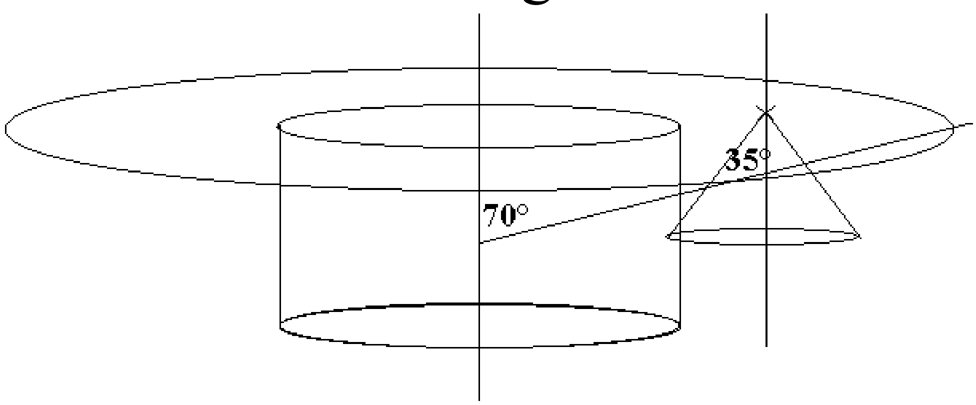
  ⇒ energy resolution of 3 %

  rate : 0.5 min^{-1}

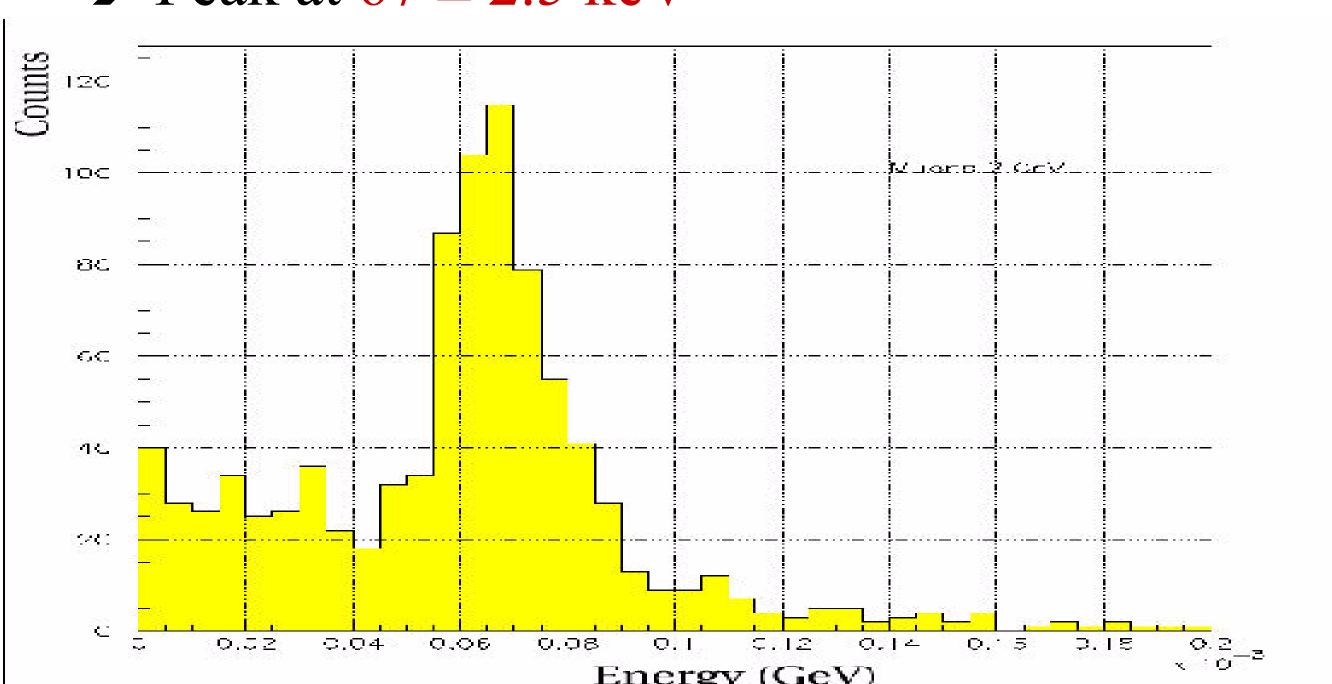
- Shift compared with the expectation value of 764 keV:
  - vortices creation (Kibble mechanism)
  - UV photons emission

Muons simulation :

- Estimate of the expectation counting rate by the single cell prototype : 0.36 min^{-1}
- Simulation of muons inside the cell with GEANT3.21 :
  - energy : 2 GeV
  - draw of the muons generator :

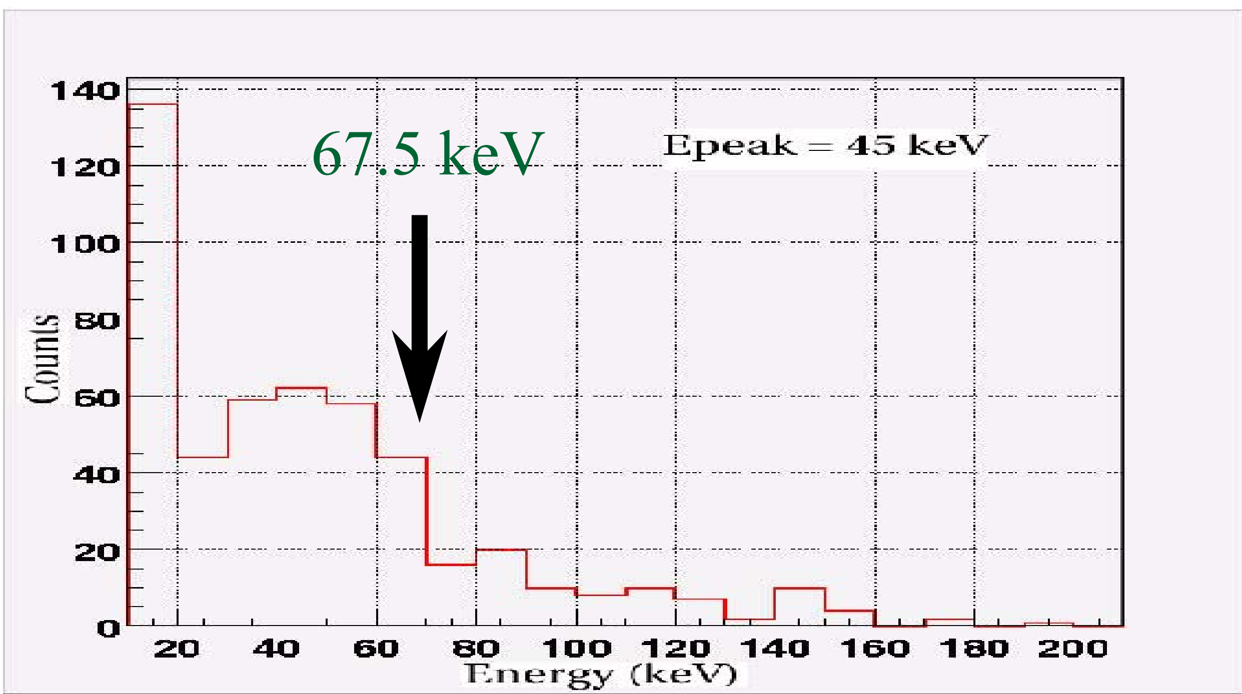


➔ Peak at 67 ± 2.5 keV



Muons spectrum :

- Acquisition time 19 h, at 100 μK
- Peak at 45 ± 5 keV
- Energies < 20 keV : numerical limitation of the data analysis procedure



- Counting rate (muons + γ) similar to estimate ~ 0.36 min^{-1} (due to the fact of a low rate of γ : ~ 0.01 min^{-1})
- Shift compared with the simulation :

➔ mechanism of UV photons emission ?

Conclusions :

- Two major contributions to background are experimentally shown :

  - clear separation of thermal neutrons

  - detection of cosmic muons

- Simulation of muons inside the detector with GEANT3.21

- Estimate of a low counting rate of γ compared with the muons one

Prospects :

- Improvement of the analysis method

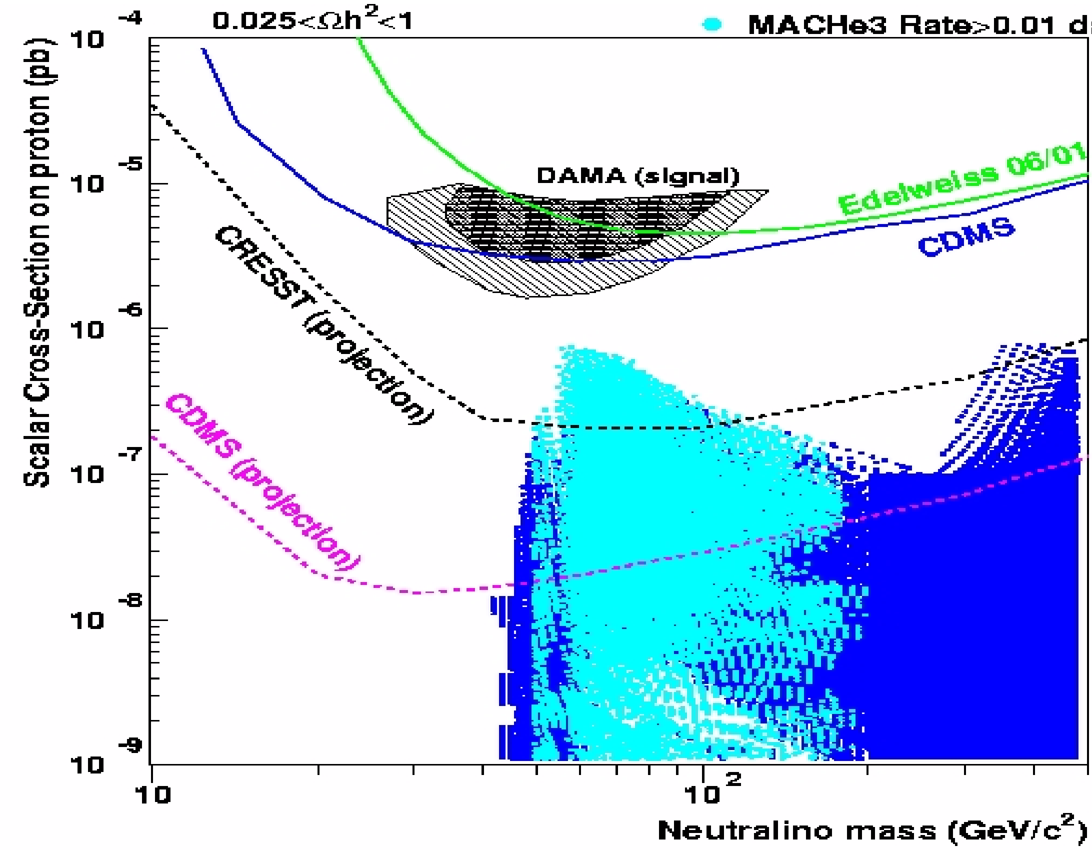
- A better understanding of background caused by micro-vibrations is necessary (shape of these peaks would be more symmetric)

- Wavelets treatment is investigated

- Calibration at low energy : electron conversion source of ^{57}Co with 7, 14, 115 and 129 keV lines is considered

- Multicellular prototype in order to use correlations among the cells to improve discrimination of events

Complementarity of MACHe3 with existing projects :



- exclusion limits from Edelweiss, CDMS experiments as well as the DAMA region
- dotted lines indicate projected limits of CRESST and CDMS experiments
- light points present SUSY models giving an event rate for MACHe3 higher than 0.01 day^{-1}

Natural radioactivity :

- Experiment with a Germanium detector :
  - ⇒ radioactive contamination: ^{40}K, ^{214}Bi, ^{214}Pb et ^{220}Ac
  - ⇒ counting rate

- GEANT3.21 simulation with :
  - Germanium cell
  - Helium cell
  - ⇒ ratio of the number of the detected counts

- Sources γ : ^{137}Cs and ^{60}Co
  - counting rate :
    - ^{137}Cs : 0.03 s^{-1}
    - ^{60}Co : 0.01 s^{-1}
  - in agreement with estimate

- γ counting rate without source :
  - 0.2 min^{-1}
  - with a lead shield (5 cm) : 0.01 min^{-1}
  - ⇒ low sensivity of the detector for γ of natural radioactivity compared with muons

χ event rate in the MACHe3 detector :

- Expression of event rate (1st approximation) :

  $$R = \sigma <v> (\rho^0 / M\chi) \times (M_{det} / m_{3He})$$

  thus,

  $$R = 1400 \times \sigma\ (pb) / M\chi\ (GeV/c^2)\ [kg^{-1}\ day^{-1}]$$

  with : $<v> \sim 270$ km s^{-1}
  $\rho^0 \sim 0.3$ GeV/c^2 cm^{-3}
  $m_{3He} = 2.81$ GeV/c^2

- For $\sigma \sim 10^{-2}$ pb and $M\chi \sim 30$ GeV/c^2

➔ $R \sim 7 \times 10^{-2}$ kg^{-1} day^{-1}

Evaluation the χ relic density in the Universe :

- χ equilibrum density : $$n_\chi^{eq} = g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi / T}$$

- Freezeout equation : $\Gamma = n_\chi \langle \sigma v \rangle = H$

resolution with $n^{eq}_\chi \Rightarrow$ $$T_{freezeout} \cong m_\chi / 20$$

(logarithmic corrrections are neglected)

- For a radiative universe : $$H(T) = 1.66\ g^{1/2} \frac{T^2}{M_{Pl}}$$

- Density per covolume is constant (adiabatic expansion) : $$\left(\frac{n_\chi}{s}\right)_0 = \left(\frac{n_\chi}{s}\right)_{freezeout}$$

with $s \cong 0.4\, g\, T^3$ and $s_0 / k \cong 3000\, cm^{-3}$

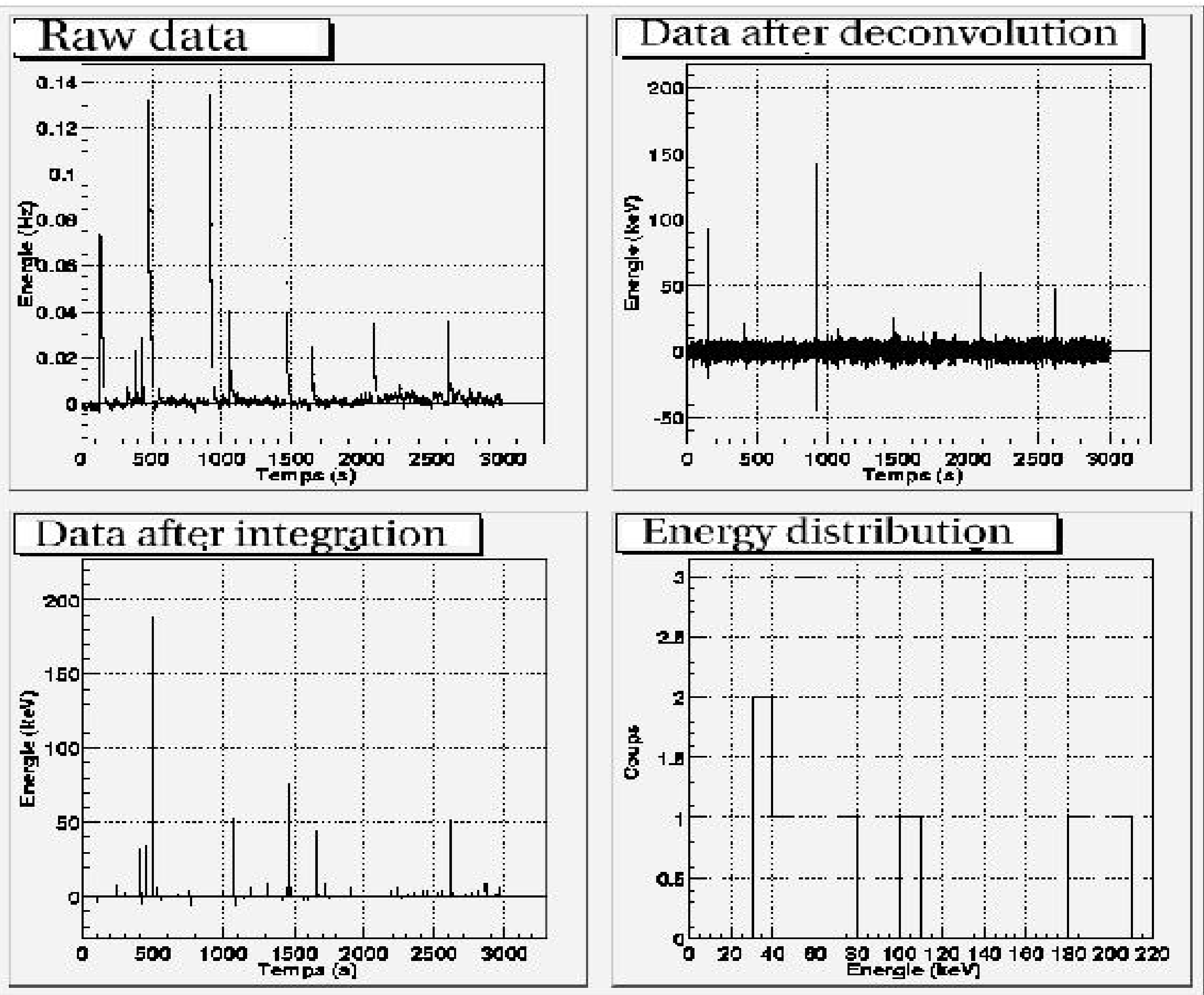
$$n_\chi = \frac{3 \times 10^{-8}}{m_\chi M_{Pl} \langle \sigma v \rangle}$$

and : $$\Omega_\chi^0 h_0^2 = \frac{O\left(10^{-27}\ cm^3\ s^{-1}\right)}{\langle \sigma v \rangle}$$

$\Rightarrow \Omega_\chi = O(10^{-1})$

Data analysis procedure in three steps :

- systematic subtraction of the low frequency modulation (polynom of order 5)
- deconvolution
- integration in order to limit the ‘‘numerical’’ noise caused by deconvolution



Principle of data analysis :

• raw spectrum f(t) : $f(t) = \int_{-\infty}^{+\infty} h(u)\, g(t-u)\, du = (h * g)$

with g(t) response function of the wire
h(t) Dirac comb

- Fourier transform of f(t) : $F(\omega) = H(\omega) \times G(\omega)$

- with inverse Fourier transform : $h(t) = TF^{-1}\left(\frac{F(\omega)}{G(\omega)}\right)$

• use of a reference peak for deconvolution :

- at equal temperature, peaks have the same shape:
  - rising time : 1 s
  - descending time (at half height) : 10 s (at 100μK)

- descending time : function of the running temperature